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Can an aircraft be piloted via sonification with an acceptable attentional cost? A comparison of blind and sighted pilots

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A B S T R A C T

In the aeronautics field, some authors have suggested that an aircraft's attitude sonification could be used by pilots to cope with spatial disorientation situations. Such a system is currently used by blind pilots to control the attitude of their aircraft. However, given the suspected higher auditory attentional capacities of blind people, the possibility for sighted individuals to use this system remains an open question. For example, its introduction may overload the auditory channel, which may in turn alter the responsiveness of pilots to infrequent but critical auditory warnings. In this study, two groups of pilots (blind versus sighted) performed a simulated flight experiment consisting of successive aircraft maneuvers, on the sole basis of an aircraft sonification. Maneuver difficulty was varied while we assessed flight performance along with subjective and electroencephalographic (EEG) measures of workload. The results showed that both groups of participants reached target-attitudes with a good accuracy. However, more complex maneuvers increased subjective workload and impaired brain responsiveness toward unexpected auditory stimuli as demonstrated by lower N1 and P3 amplitudes. Despite that the EEG signal showed a clear reorganization of the brain in the blind participants (higher alpha power), the brain responsiveness to unexpected auditory stimuli was not significantly different between the two groups. The results suggest that an auditory display might provide useful additional information to spatially disoriented pilots with normal vision. However, its use should be restricted to critical situations and simple recovery or guidance maneuvers.

1. Introduction

Sonification is commonly defined as the systematic, reproducible, and objective data-dependent generation of non-speech sounds (Kramer et al., 1999; Hermann et al., 2011). It aims to provide an auditory representation of data in order to convey meaningful information from a dataset to a listener via an auditory display (or sonic interface). Any sonification system must meet certain criteria: the sound has to reflect properties and/or relations in the input data; interactions between data and sound must be accurately defined; it must be reproducible, i.e. two identical datasets must produce structurally identical sounds and it must allow the processing of various datasets (Hermann, 2008). Sonification techniques have been employed in various application areas such as exploration of data (Delogu et al., 2010; Degara et al., 2014; Rutz et al., 2015), process monitoring (Neuhoff et al., 2000; Hermann et al., 2003) or assistive technology for the visually impaired (Kay, 1974; Edwards, 1989; Auvray et al., 2007; see Roentgen et al., 2008 for a review). In all these situations, sonification is generally needed since the continuous monitoring of critical visual information might be impossible due to attentional (e.g., vision is necessarily engaged in another direction) or sensory limitations (e.g., visual impairment).

In aeronautics, such a sonification system, namely the soundflyer, is currently used by visually impaired people. This embedded system operates the sonification of two dimensions of the aircraft attitude, i.e. its pitch and its bank angles. The pitch angle of an aircraft corresponds to the angle between its longitudinal axis

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and the horizontal plane. For instance, when an aircraft's nose is up, its pitch angle value is positive. The bank angle of an aircraft corresponds to the angle between its wings (or its lateral axis) and the horizontal plane, when viewed from the rear. The sound-flyer sonification consist in modulating the features (i.e. frequency, rhythm, inter-aural balance) of a sinusoidal pure tone which is continuously displayed to the pilot via his headphones. The pitch of the aircraft is rendered by the frequency of the pure-tone sound and the bank angle is rendered by the conjunction of the rhythm and the inter-aural balance of the sound (see section 2.2, for more details). The sound-flyer also contains a vocal module: upon request via a customized keyboard, speech synthesis can read aloud important flight parameters such as altitude, speed, vertical speed, and so on. Thanks to this system, visually impaired pilots gain monitoring and decision-making autonomy in the cockpit; they have less need to communicate with their co-pilot to access aircraft parameters. Beside the successful development of this system, used by blind pilots in real situations, laboratory studies have suggested that auditory displays could also be used by sighted pilots to exert some control over the attitude of their aircraft or to follow a given route (DeFlorez, 1936; Lyons et al., 1990; Brungart and Simpson, 2008). In particular, Brungart and Simpson (2008) have proposed that it could favor the orienting of the aircraft during spatial disorientation episodes, which are responsible for numerous fatal aviation accidents (Newman, 2007).

1.1. *Facing spatial disorientation in the cockpit*

Spatial disorientation occurs when a pilot is unable to determine the spatial position of the aircraft relative to the surface of the earth, because incomplete or competing information are coming from his visual, vestibular or proprioceptive systems (Benson, 1999). In the worst case, the compelling dimension of this perceptual conflict can lead pilots to neglect and mistrust their visual instrumentation. As such, it has been proposed that auditory redundancy of the aircraft attitude (e.g., the pitch and the bank values) could represent a valuable safety net against spatial disorientation (Brungart and Simpson, 2008). It would provide additional non-visual cues of the aircraft attitude and could help to overcome such perceptual conflicts. However, given the suspected higher auditory attentional capacities of blind people, the possibility for sighted individuals to use a sonification system remains an open question. One has to ensure that its use would remain acceptable for the auditory attentional capacities of sighted pilots, as highlighted in the Sonification Report (Kramer et al., 1999). In other words, in the context of a usability analysis, it is worth assessing whether the processing of a sonification system can interfere with other critical operations. In particular, it should not alter the ability of the brain to remain distractible (i.e. responsive to stimuli unrelated to the task at hand), especially in the cockpit where rare but possible critical auditory warnings may occur.

1.2. *Auditory attention and visual impairment*

There is a large body of evidence showing that the loss of vision or audition induces compensatory mechanisms in the remaining sensory modalities (Merabet and Pascual-Leone, 2010). Psychophysical and neuroimaging studies in both animal and human subjects have demonstrated that sensory deprivation from early developmental stages leads to functional reorganization of the brain that favors the spared modalities (Rauschecker, 1995). Such crossmodal compensation of perception is accompanied by functional reorganizations (Kujala et al., 2000) expressed as a colonization of the deprived cortical areas by the remaining modalities. In humans, brain imaging studies in blind individuals have revealed that the deprived visual cortex can be activated by auditory or tactile inputs (Sadato et al., 1996; Cohen et al., 1997; Weeks et al., 2000; Röder et al., 2002; Renier et al., 2013) thus reducing its alpha (8–12 Hz) oscillatory activity (Noebels et al., 1978; Leclerc et al., 2005; Kriegseis et al., 2006), indexing its idling state (Başar et al., 1997). Moreover, cross-modal compensation in blind people is strongly suspected to favor selective or divided auditory attention (Kujala et al., 1997; Collignon et al., 2006). For instance, Kujala et al. (1995), in an auditory-tactile task, showed that cerebral reaction to unexpected auditory events was less attention-dependent in the blind compared with the sighted. Participants in their study were presented with deviant (10%) and standard (90%) stimuli for each sensory modality. Standard and deviant stimuli differed from one another in their spatial locus of origin. They were asked to count the number of deviant stimuli for a specific sensory modality (auditory or tactile) and to ignore the ones in the other modality. Event-related potentials (ERP) for frequent and rare stimuli were recorded for the attended and the unattended sensory modalities. The results showed that the mismatch negativity component (indicative of the automatic cerebral reaction to deviant stimuli) was greater for the blind subjects compared with the sighted—*whether these stimuli were attended to or not*.

These results suggest that in cross-modal situations, blind individuals could exhibit better performance at auditory processing and might be less impaired in their ability to process additional unexpected stimuli. However, in the context of the present study, these results have to be qualified for at least two reasons. First, these studies were carried in very fundamental frameworks and do not allow to predict the effects of cross-modal compensations in more ecological situations. Indeed, many other factors such as task complexity or expertise, might interfere. Then, blind-sighted differences are often observed in response times (Kujala et al., 1997; Collignon et al., 2006) or in mismatch negativity amplitudes (e.g., Kujala et al., 1995), but not in accuracy level (see Collignon et al., 2006, p.177, for instance). Yet, in ecological situations one might find that performance is better defined by response accuracy than by a 100 ms reaction time difference. Thus, although cross-modal compensation in blind subjects is beyond doubt, it remains difficult to draw a straight prediction regarding its consequences on subjects performance, in an ecological piloting situation – which reinforces the importance of the present investigation.

1.3. *The irrelevant auditory probe technique*

In order to evaluate the cognitive demand of a task, one might probe the participant with a secondary task (Wickens, 1991). For instance, the participant can be asked to pay attention to a specific stimulus in a sound stream while performing a primary task (see Giraudet et al., 2015a for a recent example). Generally, performance of the irrelevant secondary task is thought to reflect the amount of resources left by the task of interest, thus indicating its ongoing demand (Wickens et al., 1983). This has been largely corroborated at the cerebral level, where some ERP components were found to be sensitive to the amount of available resources (Giraudet et al., 2015a). In particular, the N1 and the P3 components elicited by primary and secondary tasks stimuli often vary in amplitude, as a function of perceptual and central processing resources respectively (Kok, 2001), thus providing a valuable workload index. However, as the secondary-task method forces the participant to perform an additional irrelevant task, it can penalize mental workload assessment and interpretation. Not only does it increase the overall workload, but it can interfere with the primary task, resulting in an artificial decrease in performance at the task of interest (Ullsperger et al., 2001). Furthermore, in a real flight context, one might want to assess mental workload without disturbing the natural course of the operator's activity.

To address these limits, Papanicolaou and Johnstone (1984) proposed the "irrelevant-probe technique". In this paradigm, participants are probed with standard (frequent) and deviant (rare) sounds but do not have to respond to them. Assuming that available resources are automatically devoted to additional stimuli processing, ERP amplitudes reflect the amount of remaining processing resources (Kramer et al., 1995; Ullsperger et al., 2001; Allison and Polich, 2008; Sugimoto and Katayama, 2013). In particular, P3 amplitude for deviant compared to standard sounds is supposed to be related to shifts of attention toward unexpected events, even those not requiring an explicit response (see for example Harmony et al., 2000). Allison and Polich (2008) showed that, during a difficulty-varied video-game, most ERP component amplitudes (P2, N2 and P3) for rare tones decreased as the difficulty of the video-game increased, whether this rare tone had to be focused on or not. Interestingly, not only ERP amplitudes give indication on available attentional resources, but a recent study suggests that they can predict the participant's awareness of an auditory stimulus. For example, Giraudet et al. (2015a,b) showed that the amplitude of the P3 was correlated with the ability of participants to respond to rare target sounds during a simulated piloting task. This inability to perceive auditory stimuli has been called "inattentional deafness" (Dehais et al., 2014; Giraudet et al., 2015b).

1.4. Experimental objectives and hypotheses

The present study aimed to assess the possibility of extending the use of the sound-flyer, initially designed to help blind pilots keep their aircraft in a neutral attitude (wings flat), to sighted pilots who might be helped by the system to perform maneuvers during spatial disorientation episodes. Given the suspected higher auditory attentional capacities of blind people, we examined if the use of the sound-flyer by sighted individuals did not overload the auditory channel, which may in turn alter their responsiveness to rare but possible critical auditory warnings, especially when maneuvers are more complex. Two groups of pilots (blind and sighted) were recruited and had to perform precise maneuvers (e.g., "turn left 5°") that varied in difficulty, on the sole basis of the auditory information provided by the sound-flyer. We conducted behavioral measurements of the flight performance along with subjective (NASA-TLX) assessment. Following a neuroergonomic approach (Parasuraman, 2003), we also evaluated the potential deleterious impact of the sound-flyer on the brain responsiveness to task-unrelated auditory stimuli using the irrelevant auditory-probe technique, presented hereafter.

We hypothesized that increased difficulty maneuvers may decrease maneuver precision and increase the subjective difficulty. We also hypothesized that difficult maneuvers may reduce the responsiveness of the brain to the task-unrelated auditory stimuli. Finally, we hypothesized that the blind group should also demonstrate a higher alpha power, indexing the functional reorganization of their brain. This functional reorganization may result in higher maneuver precision and a higher responsiveness to the sounds.

2. Methods

2.1. Participants

Two groups consisting of 9 visually impaired (mean age 44.3 ± 12.5 years) and 8 sighted pilots (mean age 35.8 ± 15.6 years) were recruited from French aeroclubs. Before the experiment, all pilots signed a consent form. This consent form was read to the blind participants. To prevent any use or interference from the visual sense, even with residual capacities, all participants were blindfolded. The research was carried out fulfilling ethical requirements in accordance with the standard procedures of the University of Toulouse. Before the experiment, we tested participants for their auditory acuity using AudioConsole software and Silento Supermax headphones. All of them showed normal hearing thresholds (between 0 and 10 dB).

2.2. The sound-flyer

Aircraft sonification was supported by a simplified version of the sound-flyer developed by Thales (France). The sonification consisted in modulating a sinusoidal pure-tone as a function of the aircraft attitude that was a combination of the roll pitch angles of the aircraft. The roll angle (or bank) corresponded to the aircraft position about the longitudinal axis, positive with the right wing down. The pitch angle corresponded to the aircraft position about the lateral axis, positive with nose up. The aircraft pitch angle was positively correlated with the pure-tone frequency. An increase of one degree of the aircraft pitch angle engendered an increase of 20 Hz of the frequency of the pure-tone, and conversely for a decrease. The aircraft roll angle was transposed by the inter-aural balance and the rhythm of the tone. As the aircraft turned left/right, the pure-tone moved progressively from the center (O°) to the left/right (2°) of the auditory scene. Moreover, the rhythm of repetition of the pure-tone got faster every 5°. This setup did not allow the monitoring of bank in-between values since a particular rhythm was applied for a range of 5°. As a consequence, in-between values (e.g. a bank of seven degrees) were excluded from instructions, to avoid artificial decrease in performance (Fig. 1).

An added RB-530 Cedrus response box allowed participants to request vocal indication on the real pitch and bank current values. It was placed on the right-hand of the participant (Fig. 2). This device was used to help the participant during the training session. Its use was not allowed during the test session, except between two maneuvers, in order to help to recover a straight and level flight.

2.3. The aviation task

The experiment took place aboard the 3-axis motion (roll, pitch, and height) PEGASE flight simulator (Institut Supérieur de l'Aéronautique et de l'Espace, Toulouse, France; Fig. 2). The task consisted in performing successive precise maneuvers on the sole basis of the sound-flyer information. Each maneuver consisted in attaining a precise aircraft attitude starting from a neutral position (pitch and bank angles $\approx$ 0°). Three levels of difficulty were created, according to the number of parameters to apply. In the low-difficulty condition, the subject had to maintain a neutral attitude (baseline condition). In the medium-difficulty condition, the target-attitude was defined by either a pitch *or* a bank value; in this condition, the irrelevant parameter had to be ignored. In the high-difficulty condition, the target-attitude was defined by a pitch *and* a bank value. Irrelevant sound features were not removed from the auditory scene so that the auditory information remained equivalent across the three difficulty levels.

Target attitudes were presented to the participant at the onset of each trial by means of a synthetic voice. Pitch-target values were selected among ±3°, ±5° or ±10°. Bank-target values were chosen among ±5°, ±10°, ±20°, negative values being left-side maneuvers. Each instruction had the structure of the following example: "Next maneuver. Make a turn of five degrees to the left". On average, participants had 41 s to apply the instruction and reach the target attitude as best as they could. This duration varied slightly because of the time jitter (800 ± 400 m) between two irrelevant-probe stimulations. Once the synthetic voice had indicated the end of the maneuver, participants had 20 s to recover to a straight and

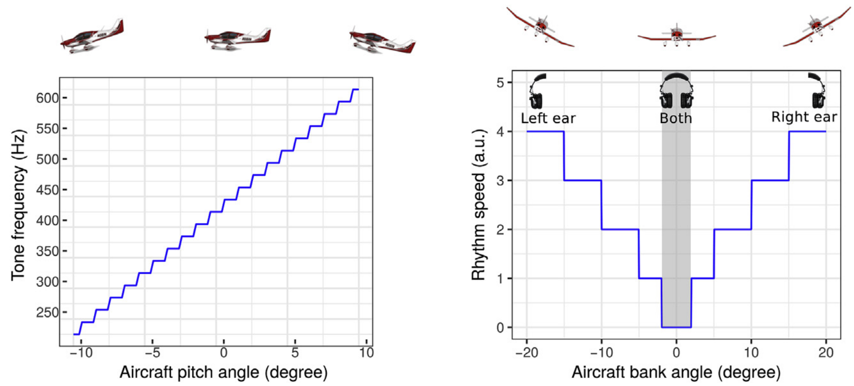

Fig. 1. The sound-flyer functioning. (A) Relationship between the aircraft pitch angle and tone frequency. (B) Relationship between the aircraft bank angle and the tone rhythm; as the aircraft turns left/right, the tone moves progressively from the center (0°) to the left/right (2°) of the auditory scene.

level flight and wait for the following maneuver. During this recovering phase, they were allowed to use vocal information if they wanted to, in order to reach the neutral attitude faster and more accurately. The performance of the participants was not recorded during this recovering phase.

2.4. *Irrelevant auditory probe stimuli*

Irrelevant-probe stimulation consisted in frequent (90%) and rare (10%) syllables (/*Ta*/or/*Ti*/) of 189 ms. We used syllables instead of sinusoidal tones to avoid frequency masking between the sound-flyer and the irrelevant probes. Given the passive paradigm, the a priori proportions (90-10) of the syllables were selected to maximize the probability of eliciting components of larger amplitude (Duncan-Johnson and Donchin, 1977). Each difficulty condition included a total of 27 rare and 143 frequent probes, as the averaging of more than 20 trials is often needed to elicit a component precisely (see Cohen et al., 1997 for an example with the P3). Time interval between two syllables ranged between 800 and 1200 ms (time jitter). Each probe sequence was randomly generated on a trial-to-trial basis, with two successive rare probes being separated by at least two frequent probes. Frequency-syllables mapping (e.g. rare-/*Ti*/or rare-/*Ta*/) was counterbalanced across subjects. Instructions and irrelevant auditory-probes stimuli were mixed with the sound-flyer sonification via a Gemini PS-540i mixing table. The resulting auditory scene was delivered to the participant in intra-auricular headphones.

2.5. *EEG recording and processing*

Electroencephalographic (EEG) data was recorded with a 128-channel Active Two Biosemi system, at a 2048 Hz sampling rate and decimated at 512 Hz before further processing using EEGLAB (version 13.4.4.b, Delorme and Makeig, 2004). The signal was re-referenced to the average of the left and right mastoids, and filtered with a band-pass of 0.2–40 Hz. For each subject, noisy channels were removed and interpolated ($M = 4.31$, $SD = 2.5$). We then rejected noisy portion of data by visual inspection of the continuous signal. This led to rejecting an average of 10.9% ($se = 0.02$) of deviant events and 10.5% ($se = 0.02$) of standard events. An independent component analysis (ICA) was performed on each dataset to identify and reject ocular artefacts (Vigário, 1997; Jung et al., 1998). This technique is commonly accepted as a reliable tool to extract ocular artefacts from EEG signal (Jutten and Herault, 1991), even in the blind who are known for presenting much higher quantity of eye movements and more variability across subjects (Flexer et al., 2005). Cleaned data was then segmented in 900 ms epochs with a 100 ms pre-stimulus baseline.

2.6. *Procedure*

After having signed a consent form, participants were given instructions for the experiment while we equipped them with the 128-channel EEG. They were equipped with the blindfold and the intra-auricular headphones. Participants were told they would have to reach precise aircraft attitudes, on the sole basis of auditory non-speech information. They were then explained the sound-flyer mechanics, i.e. the relationship between the aircraft attitude and the variation of the sound. After that, all the participants were given two training sessions. During the first session, they were instructed to use the sound-flyer freely and to focus on the relationships between the aircraft attitude and the sonification. Since the pilot

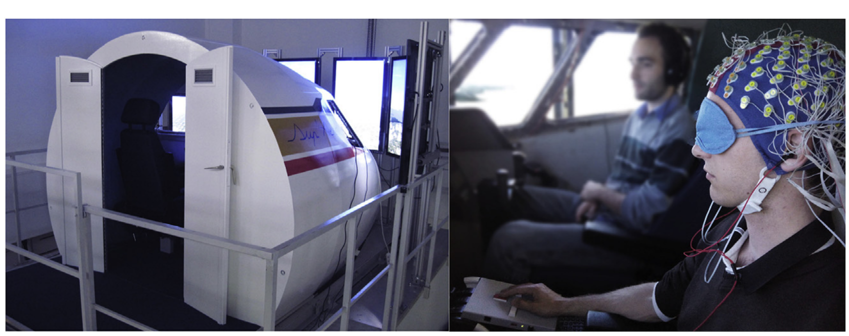

Fig. 2. The experimental setup. On the left, the flight simulator. On the right, a participant with the electroencephalographic installation, the intra-auricular earphones and the Cedrus response box.

could not rely on visual input, they had to use the vocal module if they wished to obtain accurate information on the aircraft attitude. In the second training session, the pilots had to achieve sixteen maneuvers of the three difficulty levels. During this session, instructions were provided in the same form as in the following test session. The use of the vocal module was allowed only during these two training sessions. Participants were then informed that the test session would be similar, apart from a few different details. First, they were told that irrelevant sounds would be added to the auditory scene and that they must ignore them and focus on the piloting task. They were also reminded that any use of the vocal module during a test maneuver would automatically discard the trial and that they were only allowed to use it during the recovering phase, i.e. between two trials. For the medium-difficulty level, participants were instructed to ignore the irrelevant parameter. For instance, if the maneuver was to attain a certain bank value, participants had to ignore the pitch parameter, as their performance would be computed on the sole basis of the bank parameter.

The test session was divided into twenty blocks. The first and last blocks were low-difficulty (baseline). The other 18 blocks alternated between medium and high-difficulty conditions. For the low difficulty condition, as the participants had nothing to do but maintain a level flight, we assumed that two repetitions (see Fig. 3) of this condition were sufficient to provide an accurate measure of the participant's behavior. Over the whole test session, each difficulty condition (low, medium, high) included a total of 27 deviant and 243 standard syllables. During the medium and high difficulty blocks, participants were given a break for 15 s after each of the six blocks. At the end of the test session, the EEG and the blindfold were removed from the participants and they were submitted to a French paper and pencil version (Cegarra and Morgado, 2009) of the NASA-TLX (Hart and Staveland, 1988) to evaluate subjective workload for each difficulty level. On average, a session lasted 2 h and a half (Fig. 3).

2.7. Data analyses

Statistical analyses were performed using R (3.2.4). The significance level was set at 0.05. When needed, statistical outputs were corrected for violation of sphericity with the Greenhouse Geiser method. The overall subjective workload consisted of the average of all dimension scores. A mixed analysis of variance (ANOVA) was carried out on this score, with difficulty as the repeated measure (low *vs* medium *vs* high) and group as the between factor (blind *vs* sighted). Error was computed as the mean difference between the aircraft and the target positions for the relevant parameters. For instance, when the target position was defined only by a bank value, the pitch was not included in the error computation, as the participants were explicitly allowed to ignore it. This error computation only concerned the five last seconds of each maneuver to discard some strategical effects. For instance, in the high-difficulty condition, some participants considered the two sound features sequentially, processing the two parameters one after the other. Therefore the performance corresponded to the ability to have reached a given parameter value at the end of the trial, whatever the participant strategy. The resulting values were submitted to a mixed ANOVA with difficulty as a repeated measure (low *vs* medium *vs* high), the error dimensions as a repeated measure (pitch *vs* bank) and group as the between factor (blind *vs* sighted).

For each subject, a maximum peak amplitude (μV) was computed for the N1, the P2 and the P3 components, from the three midlines sites (Fz, Cz and Pz). Fz, Cz and Pz were chosen for analysis because N1, P2 and P3 responses are typically largest on the midline locations, probably due to the fact that midline electrodes pick up both left and right hemisphere activity. This is in line with several studies which have presented recordings of midline electrodes only when examining the N1 (Kramer et al., 1995; Ullsperger et al., 2001), the P2 (Miller et al., 2011) or the P3 components (Polich, 2007). Peak amplitude was defined as the maximum negative/positive value in a given time window, the size of which was large enough to ensure correct peak detection for all subjects. Time windows were defined by visual inspection of grand averages, following the procedure given by (Handy, 2005). The N1 time-window ranged from 80 to 140 ms; the P2 time-window ranged from 200 to 260 ms and the P3 time-window ranged from 340 to 410 ms. The 30 data points (≈60 ms) surrounding the maximum peak amplitude point were averaged, resulting in a mean peak amplitude for each component. The mean peak amplitudes were submitted to a mixed ANOVA, with electrode (Fz *vs* Cz *vs* Pz), difficulty (low *vs* medium *vs* high), frequency (standard *vs* deviant) as the repeated measures and group (blind *vs* sighted) as the between factor. When needed, analyses were completed with a Tukey's HSD post-hoc. Alpha spectral power was computed as the mean spectral power for the common alpha band frequency (8–12 Hz), from O1 and O2 leads electrodes of the occipital area, where the alpha spectral-power is typically highest (Williamson et al., 1997). The resulting variable was submitted to a mixed ANOVA, with electrode (O1 *vs* O2), difficulty (low *vs* medium *vs* high) and frequency (standard *vs* deviant) as the repeated measures, and group (blind *vs* sighted) as the between factor.

3. Results

3.1. Spectral alpha-band power

There was a main effect of the group over the alpha spectral power ($10 \times \log_{10}(\mu V^2)$), $F(1,15) = 9.84$, $p = 0.007$, $\eta_p^2 = 0.40$, meaning that the sighted group presented greater spectral power ($M = 58.83$, $SEM = 0.57$) than the blind group ($M = 52.12$, $SEM = 0.26$; Fig. 4). Likewise, there was a main effect of the difficulty over the alpha spectral power, $F(2,30) = 3.43$, $p = 0.041$, $\eta_p^2 = 0.005$, such that the low difficulty condition triggered a greater spectral power ($M = 55.65$, $SEM = 0.63$) than the medium ($M = 55.27$, $SEM = 0.68$) and the high ($M = 54.92$, $SEM = 0.68$) difficulty conditions. Notably, only the low-high difference was significant ($d = 0.73$, $p = 0.014$).

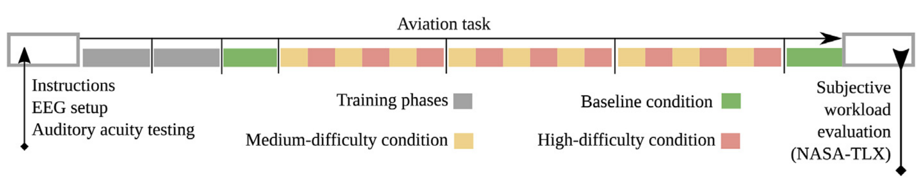

Fig. 3. The experiment timeline. Each solid vertical line represents a break given to the participant.

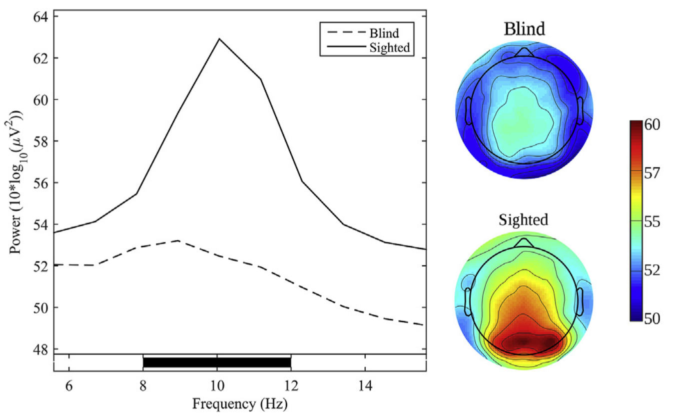

Fig. 4. Alpha spectral power topography as a function of the group. Blind–sighted difference was significant over the 8–12 Hz range.

3.2. Behavioral results

3.2.1. Performance

For the error index, we obtained a two-way interaction between the type of axis (bank *vs* pitch) and the difficulty level, $F(2,30) = 26.58$, $p < 0.001$, $\eta_p^2 = 0.16$, such that the pitch-bank difference was smaller in the low-difficulty condition ($d = 0.96$, $p = 0.19$) than in the medium ($d = 1.58$, $p = 0.003$) and the high-difficulty condition ($d = 2.58$, $p < 0.001$). This was mainly due to an error increase for the bank parameter in the medium ($M = 3.66$, $SEM = 0.60$) and the high ($M = 4.60$, $SEM = 0.45$) conditions, compared to the low difficulty condition ($M = 0.32$, $SEM = 0.14$). In contrast, the error for the pitch parameter remained somewhat constant across the three difficulty conditions (Fig. 5). Notably, there was no significant difference between the medium and the high-difficulty conditions both for the pitch ($d = 0.06$, $p = 0.99$) and the bank ($d = 0.94$, $p = 0.21$) parameters. Finally, there was no main effect of the group ($p = 0.42$, $\eta_p^2 = 0.03$) nor interactional effect between the group and the type of axis ($p = 0.61$, $\eta_p^2 = 0.002$).

3.2.2. Subjective workload

The interaction between the difficulty and the group to explain the NASA-TLX scoring variance did not exceed the significance threshold, $F(2,30) = 3.07$, $p = 0.061$, $\eta_p^2 = 0.06$. In other words the difficulty effect, whose size was large ($\eta_p^2 = 0.60$), seems not to have been affected by the group factor. However, this p value indicates a trend toward significance, that can be due either to the small size of the two samples or the unequal N per group. Furthermore, pairwise comparisons revealed that the sighted group was more sensitive to the medium-high difference than the blind group. More precisely, the sighted group gave a significantly higher score to the high compared to the medium condition ($p = 0.006$), while the blind group scorings were considered equivalent for these two conditions ($p = 0.078$). Regardless of the group, the low-medium comparisons always triggered a significant difference ($p = 0.011$), with the low condition triggering a lower score than the medium condition (Fig. 6).

3.3. Event-related potentials

3.3.1. N1 peak amplitude

Event-related grand averages are presented in (Fig. 7). A two-way interaction was obtained between the difficulty level, the syllable frequency and the electrode location, $F(4,60) = 3.85$, $p = 0.017$, $\eta_p^2 = 0.20$ (Fig. S2). At the Fz location, the N1 peak amplitude remained equivalent across the three difficulty levels for the standard syllables ($p > 0.99$ for the 3 pairwise comparisons) whereas the deviant syllables elicited significantly smaller amplitudes in the high than in the low-difficulty conditions ($p = 0.025$). Low-medium and medium-high differences for the deviant syllables were not significant ($p > 0.34$ for the two pairwise comparisons).

At the Cz location, where the N1 amplitudes were the largest, the N1 amplitude for the standard syllables ($M = -1.70$, $SEM = 0.22$) did not significantly vary across the three difficulty conditions ($p > 0.99$ for the 3 pairwise comparisons). Seemingly, it did not vary for the deviant syllables ($M = -3.01$, $SEM = 0.37$, $p > 0.79$ for the 3 pairwise comparisons). Plus the standard-deviant differences were not significant for any difficulty level ($p > 0.13$ for the 3 pairwise comparisons). There were no significant difference to report at the Pz location site. Notably, the N1 component was centrally distributed over the scalp. Finally, there was no main nor interactional effect of the group over the N1 amplitude.

3.3.2. P2 peak amplitude

No two-way nor one-way interactions were obtained for the P2 peak amplitude. Only the electrode location had a main effect over

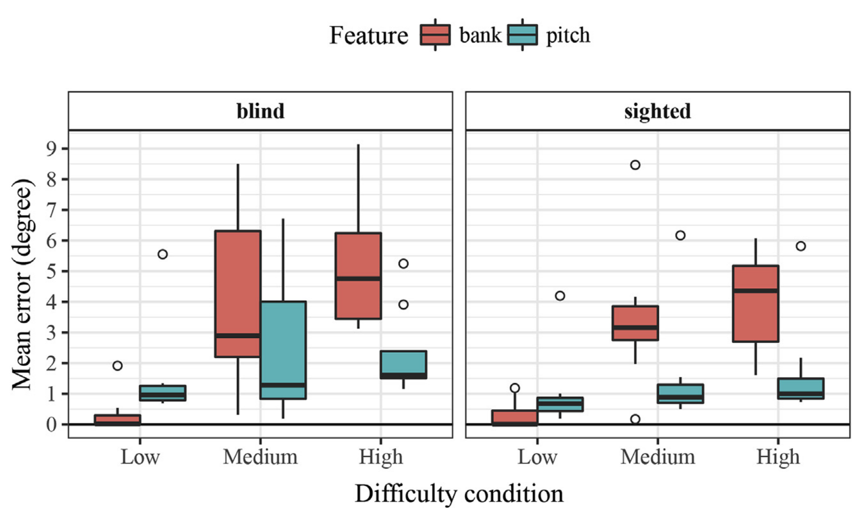

Fig. 5. Mean error (in degree) as a function of the difficulty level and the considered parameter (pitch *vs* bank).

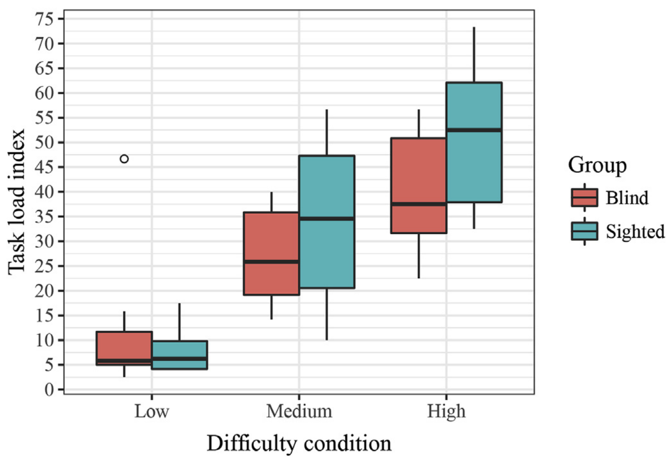

Fig. 6. Task Load scorings as a function of the group and the difficulty level.

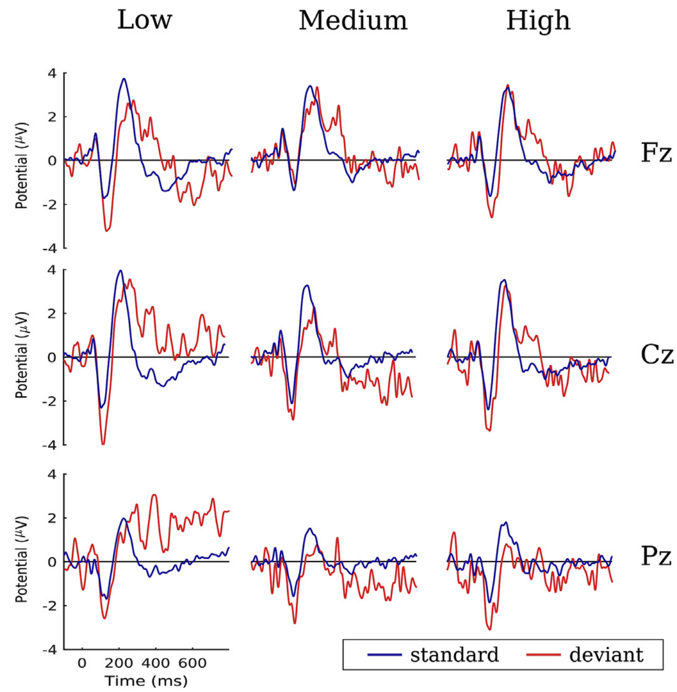

Fig. 7. ERP grand averages for Fz, Cz and Pz as a function of the difficulty level and the syllable frequency.

the component maximum amplitude, F(2,30) = 20.64, $p < 0.001$, $\eta_p^2 = 0.58$, with the Fz (M = 3.23, SEM = 0.25) and the Cz (M = 3.17, SEM = 0.27) eliciting larger peak amplitudes than the Pz location (M = 1.58, SEM = 0.21). The Pz-Fz difference was significant (d = 1.65, $p < 0.001$), like the Pz-Cz difference (d = 1.59, $p < 0.001$). Conversely, there was no significant difference between the Fz and the Cz locations (d = 0.06, $p = 0.97$). This resulted in a fronto-central distribution of the positivity illustrated by a scalp map topography. There was no main nor interactional effect of the group over the P2 peak amplitude.

3.3.3. *P3 peak amplitude*

For the P3 we obtained two distinct two-way interactions. First, there was an interaction between the difficulty level and the syllable frequency, F(2,30) = 3.79, $p = 0.034$, $\eta_p^2 = 0.20$, such that globally, the standard-deviant difference was significant in the low-difficulty condition (d = 2.85, $p < 0.001$) but not in the medium (d = 1.19, $p = 0.10$) nor in the high-difficulty (d = 1.03, $p = 0.22$) conditions. This was due to a global decrease of the P3 peak amplitude for the deviant syllables in the medium and the high-difficulty conditions (Fig. S2). Secondly, there was an interaction between the difficulty level and the electrode location, F(4,60) = 4.92, $p = 0.008$, $\eta_p^2 = 0.25$, such that as the difficulty increased, the P3 peak amplitude tended to increase at the Fz location but not at the Cz nor the Pz locations where it tended to decrease. However, post-hoc analysis revealed that none of the low-medium, low-high or medium-high differences was significant, at any location site ($p > 0.36$ for the 9 pairwise comparisons). Finally there was no significant three-way interaction to report, plus the group had no main nor interactional effect.

4. Discussion

The present study aimed to assess the usability of sonification in the cockpit, especially in sighted pilots who might suffer from spatial disorientation. First, we evaluated the ability of the pilots to use this auditory display to perform flight maneuvers that varied in difficulty. In order to index the cerebral functional reorganization ensuing the visual deprivation in the blind group, we measured the alpha spectral power related to the occipital area. Then, we tested if the use of such an auditory display impaired auditory attention toward other auditory rare events, i.e. preservation of brain distractibility toward unexpected sounds (e.g. alarms), especially when task load was high.

The results showed that more challenging maneuvers decreased maneuver precision and increased the subjective difficulty. The increased difficulty maneuver reduced the responsiveness of the brain to the task-unrelated auditory stimuli. Despite the fact that the blind group demonstrated a higher alpha power, indexing the functional reorganization of their brain, we find neither better performance nor a higher responsiveness to the irrelevant probes in this group in comparison to the sighted pilots.

4.1. *Usability under various difficulty levels*

We evaluated how the level of difficulty of the manipulation would impact the usability of the sound-flyer in terms of performance and responsiveness to irrelevant auditory probes. Performance for the low-difficulty condition differed significantly from the other two difficulty conditions, especially for the bank parameters the error of which increased along with the demand. On the other hand, there were no differences in performance between the medium and the high difficulty conditions, although participants reported a greater subjective workload for the high than for the medium difficulty condition. This is not surprising since during resource-limited tasks, performance and subjective measures of workload can be dissociated, especially when resource demand is much less than the total resources available ("underload" situation, Yeh and Wickens, 1988). Furthermore, it is commonly assumed that subjective workload is strongly related to the amount of resources that are invested in the task, in particular the amount of information held in working memory (Navon and Gopher, 1979; Yeh and Wickens, 1988). Thus, we assume that in our high-difficulty condition, participants invested more (available) resources to prevent performance decrement, hence reporting a greater subjective workload for this condition while maintaining equivalent performance. The decrease in performance for the bank parameter can be attributed to a difference in the resolution provided by the sound-flyer. As explained in the introduction, the same rhythm is applied for a range of five bank degrees (e.g., from 5° to 10°), making it difficult to have the same accuracy as for the pitch parameter. Thus, we can advance that this decrease in performance was partly due to the sonification itself.

Then, it was found that, under the irrelevant-probe stimulation (Papanicolaou and Johnstone, 1984) both the N1 and the P3 components were sensitive to the difficulty manipulations. The N1 amplitude was mainly impacted by the syllable frequency, and was affected by the difficulty level at the sole Fz location. For instance, at Fz, there was almost no difference in the N1 amplitude between the deviant and the standard syllables for the most difficult condition. Regarding the P3, increasing the difficulty led to a decreased amplitude solely for the deviant syllables. The P3 component is commonly decomposed into a P3a and a P3b subcomponents. The P3a (or novelty P3) has generally a frontocentral distribution and is elicited by novel, non-target stimuli, reflecting involuntary orientation of attention toward stimulus novelty. The P3b is associated with the potential further processing of the attention-driven stimulus, in the temporal and parietal structures (Squires et al., 1975; Polich, 2007). During the aviation task, participants did not have to overtly respond to the syllables. Thus, it is likely that the P3 amplitude modulation that we observed here was attributable to its P3a subcomponent. Finally, the P2 component was not affected by the difficulty level nor by the syllable frequency such that, following Kenemans et al. (1992), we suggest that P2 and P3 reflect distinct stages of attention orienting to deviant irrelevant probes in which only the latter P3 process is capacity−limited. These results suggest that automatic auditory change detection can be affected by the auditory demand of the task at hand (Berti and Schröger, 2003; Harmony et al., 2000) and come to complete previous evidence that an increase in mental workload can affect information processing, at early and late stages (Parasuraman, 1980; Kramer et al., 1995; Ullsperger et al., 2001). This was reflected by a decreased P3 amplitude for the deviant tones for the more difficult conditions. As for the N1, it is possible that, as the syllables were totally irrelevant to the task, an increase in the primary task load led to a diminishing of the sensory gating for the non-focal irrelevant sounds, then leading to deplete the change detection process. In more general terms, the increase in auditory load of the relevant task led to dimming the perception of irrelevant-probes, resulting in a weaker standard/deviant comparison process. Incidentally, the presents results are a good demonstration of the efficiency of the irrelevant-probe technique to assess mental distractibility without interfering with the task at hand (Ullsperger et al., 2001).

4.2. No major impact of blindness

A main finding of this study was that both groups of pilots performed maneuvers with a good precision ($\approx$2 degrees of error). Plus we found that the blind group showed a lower alpha spectral power than the sighted group at the O1 and the O2 electrode locations. As previously shown (Renier et al., 2013), it suggests an extra-recruitment of the brain occipital areas for non-visual processing in the blind group. More precisely, it brings to light the specificity of the blind group at a cerebral level and strengthens the idea that alpha activity can actually index the idling state of a specific brain area and be a reliable indicator of the cerebral functional reorganization following visual deprivation (Kriegseis et al., 2006). In spite of this cerebral specificity and their high familiarity level with the sound-flyer system, blind people showed equivalent flight performance as the sighted pilots. In other words, performance to the task with this simplified version of the sound-flyer was not determined by the level of expertise. These behavioral results constitute evidence that pilots processed accurately auditory information to exert control over the aircraft attitude. This complements previous evidence that, in absence of reliable visual information, auditory displays can be used either to fly an aircraft in a stable manner (DeFlorez, 1936) or to rapidly recover a level flight from a hazardous position (Simpson et al., 2008). Here, the pilots were able to attain various flight attitudes starting from a straight and level flight, and with quite a good precision. To our knowledge, this is the first experiment demonstrating that pilots can process auditory information, in order to identify and reach a non-neutral aircraft attitude.

Moreover, the workload induced by the use of the sound-flyer was not mainly affected by visual impairment. Though we observed little differences in the way the two groups evaluated subjective workload for the various level of difficulty. More precisely, the sighted group gave a significantly higher score to the high compared to the medium condition, while the blind group rated these two difficulty levels as triggering equivalent workload levels. Yet this difference was marginal as subjective ratings were predominantly affected by the number of sound features to process and by the technical limitations of the sonification itself (resolution). These technical constraints should be corrected in the future to ensure a better overall usability of the sound-flyer. In particular, as pointed out by Brungart and Simpson (2008), an auditory attitude indicator like the sound-flyer should provide an intuitive anchor point for a straight and level flight. So far the sound-flyer does not meet this criteria since the pilots have to memorize an arbitrary frequency that corresponds to a null pitch angle value. Notably, we did not notice any group impact over ERPs peak amplitude in spite of their presupposed auditory attentional advantage. This suggests that cortical reorganization of the “blind brain”, as indexed by the alpha spectral power, did not significantly favor auditory processing of irrelevant syllables in the present situation.

4.3. Limits

There are several limitations to this study. First of all, the piloting task as well as the auditory display were simplified. Piloting was focused on the monitoring of only two aircraft parameters (pitch and bank) in the most complex conditions, the other parameters (vertical speed, cap …) being managed by the auto-pilot.

Then we were forced to constitute two small samples ($N \leq 9$) due to the scarcity of the blind pilot population which may have affected the statistical power of our results. Moreover, sound-flyer experts were necessarily blind people, so that it was impossible to conclude about the relative role of expertise *vs* the auditory attentional skills of the pilots. In the future, it is worthwhile to control expertise as well as auditory skills more accurately, to help disentangle these two factors.

During this experiment, all the participants were blindfolded so that it is impossible to come to any final conclusion about the possibility of using the sound-flyer in an operational situation to orient one's aircraft. However the possibility to use the sound-flyer effectively when it is the only source of information available, gives hope about the possibility to use it in conjunction with other inputs such as visual information. More experiments are needed to ensure that auditory information could support a better orienting of the aircraft in real situations, where pilots have many other (visual, auditory) inputs to process.

4.4. Conclusion

We assessed the usability of a sonification system in the cockpit and its relevance to cope with spatial orientation within an aircraft. We found that both pilot groups (sighted and blind) showed an acceptable maneuver precision. Nevertheless, the sonification processing led to a mitigated responsiveness to other additional auditory stimuli at early ($\approx$110 ms) and late ($\approx$340 ms) stages, especially as task difficulty increased.

Despite clear evidence of a functional reorganization of the brain in the blind group, as indexed by higher alpha power in the occipital regions, flight performance and brain responsiveness to the additional auditory stimuli did not significantly differ between the two groups. However, we noted a near significant difference in the way the two groups assessed subjective workload. While the sighted group assigned a higher average score to the high-difficulty condition compared to the medium-difficulty condition, the group of blind pilots considered that both levels of difficulty triggered equivalent workload levels.

Finally, auditory displays – such as the sound-flyer – may provide usable auditory information even with little training, which could help pilots during spatial disorientation episodes. However, attenuated capacity to process unexpected auditory stimuli must be taken into account, particularly if the sonification system is deployed in more complex applications, where unexpected auditory events (e.g., alarms) might occur and should not be missed (Dehais et al., 2014).

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.apergo.2017.03.001.

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